Future Spacecraft Missions for Planetary Defense Preparation

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Introduction

In this paper we recommend the next three spacecraft missions that should be flown to advance our planetary defense capabilities. These missions represent the minimum that should be done within the time horizon of the Planetary Science and Astrobiology Decadal Survey 2023-2032. Additional missions should be defined and flown over time to continue improving planetary defense preparedness. The next three planetary defense missions recommended here include: a dedicated space-based infrared (IR) near-Earth object (NEO) survey telescope (Mainzer, 2020 & 2020a); a spacecraft designed to demonstrate rapid-response NEO reconnaissance by studying the Potentially Hazardous Asteroid (PHA) Apophis (Binzel et al., 2020); and a spacecraft to demonstrate mitigation techniques for deflecting or disrupting an NEO (Barbee et al. 2018).

Our recommendations for these missions follow from actions in our nation's National Near-Earth Object Preparedness Strategy and Action Plan (NSTC, 2018), hereinafter denoted as NNPSAP for brevity. The NNPSAP describes specific actions currently assigned to U.S. government agencies for improving preparedness to effectively and reliably execute planetary defense.

There are currently two planetary defense spacecraft missions in active development, both of which predate the NNPSAP but are fully compatible with the actions it assigns. The first of those missions is NASA's Double Asteroid Redirection Test (DART) mission (Agrusa et al., 2020; Cheng et al., 2018; Stickle et al., 2020), which is being managed and built by the Johns Hopkins University Applied Physics Laboratory (JHUAPL). DART is currently on schedule to launch during the summer of 2021. It will perform the first demonstration of the kinetic impactor technique for deflecting a hazardous NEO by intercepting and colliding with Dimorphos, the ~150-meter sized smaller secondary body of the binary PHA Didymos.

The second planetary defense mission currently in development is a space-based IR NEO survey telescope known as the NEO Surveillance Mission (NEOSM) (Mainzer, 2020 & 2020a). NEOSM is currently in formulation and preparing to transition to Phase B, with the Key Decision Point B review currently planned to occur during the fall of 2020 (Mainzer, 2020a). The launch date for NEOSM depends on its annual funding profile. The optimal funding profile would include $90M in Fiscal Year 2021 (FY21) and would enable launch during the year 2025 (Mainzer, 2020a).

We recommend establishing an ongoing line of space missions and research activities dedicated to planetary defense. A funding level of approximately $200-250M per year, up from $150M in 2020, would provide enough funding for NEOSM and other planetary defense missions that would develop and expand U.S. NEO reconnaissance systems and mitigation techniques (Mainzer, 2020).

First Priority: The NEO Surveillance Mission (NEOSM)

We recommend that the next planetary defense spacecraft mission after DART be NASA's proposed NEOSM. Our current understanding of the NEO population, the risk of NEO impacts with Earth, and the rationale behind flying NEOSM as the next planetary defense mission are all well described in (Mainzer, 2020). NEOSM is the next priority to be pursued for a planetary defense flight mission due to the high priority of identifying, as early as possible, potential Earth impactors among the many undiscovered NEOs predicted by our NEO population models.

Current NEO population estimates indicate that over 90% of ~1000 NEOs approximately 1 km in size or larger have been discovered and pose no threat of Earth impact within at least the next century. However, the population model also predicts that there is a total of ~25,000 NEOs between ~140 m and ~1 km in size, and to date only about 35% (~9,100) of those have been discovered and found to not pose an Earth impact threat. Completing the survey of NEOs >140 m in size is a high priority, as any of the ~15,900 undiscovered NEOs several hundred meters in size could cause regional- to continental-scale damage during an Earth impact. NEOs <140 m in size are capable of causing serious damage and harm at smaller, more localized scales that may still span large metropolitan areas. Thus far, ~13,000 NEOs <140 m in size have been discovered, none of which pose a threat of Earth impact within the foreseeable future. However, the number of NEOs <140 m in size is likely at least several million, if you count NEOs down to ~10 m size (at which point an NEO will likely explode in the upper atmosphere rather than cause ground damage).

U.S. Congress-mandated NEO searches are currently focused on meeting the objective of discovering and cataloguing >90% of NEOs >140 m in size (Mainzer, 2020; Stokes et al., 2003 & 2017). Multiple studies of the topic, including the most recent one, which was conducted by the National Academy of Sciences (NASEM, 2019), have found that a space-based IR NEO survey telescope with the specifications of NEOSM will, in combination with the Rubin Observatory (formerly Large Synoptic Survey Telescope (LSST)), reach the >90% of >140 m NEOs discovery goal within about 10 years of survey operations (Mainzer, 2020).

Second Priority: Rapid-Response NEO Reconnaissance Missions

When an NEO with a sufficiently concerning near-term probability of Earth impact is discovered, it will be important to acquire data about the NEO as quickly as possible using both remote observations and in situ spacecraft reconnaissance missions. Those data must be sufficient to properly inform modeling of the potential Earth impact effects/consequences, analysis of mitigation mission options and their costs and associated risks, and emergency management/disaster response planning. A rapidly deployed reconnaissance mission can quickly confirm whether a potentially Earth-impacting NEO will miss Earth rather than collide. If the NEO is indeed on an Earth collision course, then acquiring that information quickly will enable earlier mitigation actions. If the NEO will naturally miss the Earth, learning that quickly will prevent a great deal of drawn-out uncertainty, wasted resources, societal/political/economic upheaval in potential impact zones, etc. This is further supported in the NNPSAP, where the need for rapid-response NEO reconnaissance spacecraft mission capability development is identified (NSTC, 2018). A mission currently in development whose design may prove very relevant to rapid-response NEO reconnaissance spacecraft design is the Janus mission, which is a small spacecraft mission in NASA's SIMPLEx program designed to collect data on two binary asteroids during flybys (Scheeres et al., 2020).

Therefore, we recommend that the next planetary defense spacecraft mission to be developed after NEOSM be a reconnaissance mission featuring a relatively small but sufficiently capable spacecraft that could plausibly be rapidly readied for launch and deployed quickly during an operational planetary defense scenario. The instrumentation chosen for the spacecraft should be informed by ongoing research into the prioritized NEO characterization needs for planetary defense purposes, as described in (Barbee et al., 2020; Abell et al., 2020). While a variety of candidate target NEOs for a reconnaissance demonstration mission may be identified from among the currently known NEOs, one in particular stands out as a unique and compelling opportunity: the PHA Apophis (Binzel et al., 2020).

Apophis: An Opportunity to Demonstrate Potentially Hazardous NEO Reconnaissance

Apophis is ~340-m-size PHA (Brozović et al., 2018) that will make a historic close approach of Earth on April 13th, 2029. During this close approach, Apophis will pass within ~31,300 km of Earth's surface, which is closer than our geosynchronous orbit satellites. We know of no other similarly close Earth encounter by a similarly sized asteroid within the next century. This is a truly singular—*in fact, once in a lifetime*—opportunity to observe planetary encounter effects on a minor planet using ground-based assets, remote space-based assets, and our recommended in situ rapid-response NEO reconnaissance spacecraft demonstration mission. The effects on Apophis due to the close Earth encounter include tidally-induced changes to Apophis' spin state and possible seismic activity that could lead to surface changes. Previous radar observations of Apophis revealed that it is likely a bilobate-contact binary in shape (Brozović et al., 2018). About 15% of NEAs with diameters larger than 200 m are expected to be contact binaries, similar in abundance to the true binaries (Benner et al., 2015).

Planetary radar is anticipated to produce excellent results for Apophis. Apophis will have moderately close encounters with Earth in 2020, 2021, and 2028. In 2029, Apophis will be the strongest NEO target since radar observations began in the 1960s. It will be detectable by radars used to study Earth's atmosphere and orbital debris. Long-wavelength radars may be able to map the subsurface of Apophis to depths of 15-20 m or more. Goldstone and Arecibo can image full rotations of Apophis, pre- and post-flyby, with 1.875-m and 7.5-m resolutions, respectively. Radar may be able to detect centimeter- or decimeter-sized particles lifting off from Apophis' surface, as has been observed during the OSIRIS-REx mission to the PHA Bennu (Lauretta et al., 2019).

Several study teams have developed designs for small spacecraft missions to study Apophis; the Asteroid Probe Experiment Mission (APEX) in Plescia et al. (2018) and a NASA Goddard Space Flight Center (GSFC) design (Barbee et al., 2020a) are examples. An Apophis mission will generally require by late 2025, so NASA will need to begin development of an Apophis mission relatively soon. The GSFC mission design includes a flyby of Apophis prior to rendezvous with Apophis several months before Earth encounter. Comparison of flyby and rendezvous data sets will help characterize the ability of high-speed NEO flyby encounters to provide sufficiently complete and accurate data to support planetary defense operations. Comparison of all collected data—in situ flyby data, in situ rendezvous data, and all of the ground-based and space-based remote data—will enable synergistic calibration of all data sets and their interpretations, thereby advancing our understanding of how to best interpret and utilize future remotely collected datasets for planetary science and planetary defense.

Third Priority: Next Steps in Testing and Demonstration of NEO Deflection/Disruption Techniques and Technologies

Key challenges for NEO deflection/disruption systems include reliable and accurate autonomous onboard terminal guidance while attempting to intercept NEOs. Three candidate NEO threat mitigation techniques have been found in multiple studies to be the most conceptually mature: kinetic impactors for NEO deflection, nuclear explosive devices (NEDs) for NEO deflection or disruption, and gravity tractors for NEO deflection (NASA, 2007; NRC, 2010; NSTC, 2018).

The critical performance regime of ~5–20+ km/s intercept speeds vs. NEOs as small as ~50–100 m, possibly with suboptimal solar illumination and irregular NEO shape silhouettes (Dearborn et al., 2020), has not yet been demonstrated in spacecraft flight missions. Being able to reliably intercept such small NEOs is important because smaller NEOs are exponentially more numerous than larger NEOs, so we are statistically more likely to face an impact threat from a smaller NEO, e.g., an NEO in the ~150 m or smaller size range. Barbee et al. (2015) surveyed the history of spacecraft missions that performed high-speed flybys of asteroids and comets, finding that the smallest of those objects were on the order of ~2000 m in size, much larger than the NEO size range of interest for planetary defense. Additionally, only one of those missions was intended to strike its target: the Deep Impact mission of 2005. Deep Impact's deployable impactor succeeded in striking the approximately 7,600 × 4,900 m nucleus of comet 9P/Tempel 1 at ~10.2 km/s. However, Deep Impact was a science mission, not a planetary defense mission, and its target comet nucleus was much larger than the smaller size NEOs of most interest for planetary defense.

The DART mission currently planned for launch during summer 2021 will demonstrate the capability to acquire, track, and intercept a ~150-m-size NEO target—Dimorphos, the smaller secondary member of the Didymos binary NEA system (Naidu et al., 2020)—with a relative speed at intercept of ~6 km/s. The DART mission is intended to produce a diagnostic change in the secondary body's orbit about the primary body within the binary asteroid system, *not* an Earth deflection-scale change in the binary asteroid's heliocentric orbit (Cheng et al., 2018).

The DART mission will also provide our first insight into the momentum enhancement factor ("beta," β) expected from NEO material ejected from the crater made in the NEO's surface by the kinetic impactor spacecraft (Stickle et al., 2020). The β effect can change the NEO's velocity beyond basic conservation of linear momentum effects; however, β is currently not well understood due to lack of any in situ testing and characterization on NEOs. Subsequent kinetic impactor demonstration missions would further characterize β for different combinations of relevant parameters such as NEO physical properties. Understanding the expected behavior of β is important for accurately planning attempts to deflect NEOs via kinetic impactor spacecraft.

The next NEO mitigation technology demonstration mission after DART may advance the state of the art in kinetic impactor technology in the following ways: targeting a lone (and harmless) NEO, rather than the secondary member of a binary asteroid; targeting a smaller NEO, e.g., ~50–100 m in diameter; intercepting the NEO at a higher relative speed, e.g., ~10–15 km/s; carrying sufficient mass such that, in combination with the higher intercept speed, the deflection of the target NEO's heliocentric orbit will be measurable and similar in magnitude to deflections that may be required during an actual planetary defense scenario; providing a second data point for β that extends into a new regime of impacting spacecraft momentum and target NEO characteristics.

The use of nuclear explosive devices (NEDs) to deflect or disrupt NEOs for planetary defense purposes is also currently under investigation (NSTC, 2018; Dearborn et al., 2020). The post-DART kinetic impactor mission described above has the potential to *simultaneously* advance technological readiness for deploying an NED to an NEO if the spacecraft mission has the following additional features (Barbee et al. 2018).

- It carries a NED simulator package that replicates all features/interfaces of an actual NED payload package as it would be loaded into a planetary defense spacecraft, *but* *without* *any actual nuclear device or nuclear material of any kind*. In place of the nuclear device / nuclear material would be inert material with the same interfaces, circuitry, mass properties (i.e., enveloping dimensions, total mass, moments of inertia, etc.), and so on, as the NED would have. All of the NED handling procedures and protocols, both between agencies, and within NASA, could be fully exercised and validated by treating the inert NED simulator package in the exact same manner that an actual NED would be treated. Note that because there is no nuclear payload in this mission, it is in full compliance with all relevant international treaties as they are currently written.
- Carrying the NED simulator package will allow the spacecraft to test and demonstrate all aspects of a high-speed intercept standoff NED deployment versus an NEO, except actual NED detonation, of course. This would fully exercise the ability of the spacecraft systems to sense, with sufficient accuracy and speed, the distance to the NEO during the very high-speed approach and process the associated commands to detonate the NED at the correct distance from the NEO's surface. In a real scenario, deploying the NED after NEO rendezvous is generally preferred. However, a real scenario might only permit the more stressing case of NED deployment during high-speed intercept; hence we are motivated to be prepared for it.
- Telemetry from the mission could confirm whether all of those processes executed correctly and whether the NED would indeed have detonated within the range of acceptable distances from the NEO's surface for mission success.
- This flight test mission also provides an opportunity to fully specify, test, and demonstrate all of the physical, electronic, and information security systems and protocols that would be in place for a mission that includes an actual NED.

Summary of Recommendations

In closing, we encourage the inclusion of the following recommendations in the planetary defense portion of the forthcoming Planetary Science and Astrobiology Decadal Survey 2023-2032. These may be accompanied by as much detail as may be needed from the previous sections.

- Establish an ongoing line of space missions and research activities dedicated to planetary defense, with a funding level of approximately $200M per year (Mainzer, 2020).
- The next planetary defense mission that should be developed and flown is the Near-Earth Object Surveillance Mission (NEOSM), which, in combination with the Rubin Observatory, can reach the congressionally-mandated goal of discovering >90% of the >140-m NEO population within about 10 years of survey operations (Mainzer, 2020). [Helps address all of Goal 1 in the NNPSAP (Actions 1.1—1.4).]
- Fly a spacecraft mission to an NEO to demonstrate rapid-response NEO reconnaissance capabilities, as a step towards establishing operational rapid-response NEO reconnaissance systems. This could be a spacecraft mission such as the one described here to the PHA Apophis during its upcoming historic close approach of Earth during April 2029. [Helps address NNPSAP Actions 3.1 and 3.3.]
- Fly a combination kinetic impactor / nuclear explosive device (NED) system spacecraft mission using a simulated NED device that lacks a nuclear payload and serves as a technology demonstration, ***not a live NED*** **deflection/disruption** demonstration. This

follow-on post-DART mission would demonstrate (a) increased guidance, navigation, and control capabilities under more challenging circumstances; (b) a larger-than-DART-scale impact that provides an additional data point for understanding impactor momentum enhancement factor β; and (c) operational factors, instrumentation, sensing, commanding, security, etc., for a successful standoff NED detonation during a high-speed NEO intercept, but without involving any actual nuclear device or nuclear material. It should be noted that, for political reasons, in-space testing of NEDs is deliberately deferred to a future discussion. [Helps address NNPSAP Action 3.7.]

These recommended missions represent the minimum necessary to appropriately address some of the actions assigned in the NNPSAP during the time horizon of the forthcoming Planetary Science and Astrobiology Decadal Survey 2023-2032. Additional missions will be needed over time to further address the NNPSAP actions and continually improve our planetary defense preparedness.

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